

The First Dark Microhalos

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Earth-mass dark matter halos are likely to have been the first bound structures to form in the Universe. Whether such objects have survived to the present day in galaxies depends on, among other factors, the rate of encounters with normal stars. In this letter, we estimate the amount of tidal heating and mass loss in microhalos as a result of stellar encounters. We find that while microhalos are only mildly heated in dwarf galaxies of low stellar density, and they should have been completely destroyed in bulge or M32-like regions of high stellar density. In disk galaxies, such as the Milky Way, the disruption rate depends strongly on the orbital parameters of the microhalo; while stochastic radial orbits in triaxial Galactic potential are destroyed first, systems on non-planar retrograde orbits with large pericenters survive the longest. Since many microhalos lose a significant fraction of their material to unbound tidal streams, the final dark matter distribution in the solar neighborhood is better described as a superposition of microstreams rather than as a set of discrete spherical clumps in an otherwise homogeneous medium. Different morphologies of microhalos have implications for direct and indirect dark matter detection experiments.

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Introduction: Cold dark matter (CDM) has had considerable success in accounting for the observed large scale structure of our Universe. On galactic and sub-galactic scales, however, the abundance of low-mass structure and the degree of concentration of dark matter halos predicted by CDM simulations have provoked a considerable amount of discussion. To help clarify how CDM behaves on the smallest scales, Diemand and collaborators recently performed the highest resolution numerical simulations of dark matter clustering to date [1]. These simulations start with an initial spectrum of density fluctuations extending down to the free-streaming mass of the dark matter candidate, which for a generic weakly interacting 100 GeV particle (such as a supersymmetric neutralino) is roughly $\sim 10^{-6} (t_{fo}/10^{-8}s)^{7/4} M_{\odot}$, where freeze-out occurs at an epoch $t_{fo} \sim 10^{-8} (m_{\chi}/100 \text{ GeV}) s$. As expected from scaling the results of simulations on larger scales, fluctuations in this initial distribution collapse and virialize to form structures with roughly 200 times the background density at a redshift of $z \sim 50$. This first generation of ‘microhalos’ survives to some degree as substructure in the larger halos that form subsequently in the simulations. Extrapolating to the present-day, Diemand *et al.* suggest that 10^{15} Earth-mass clumps should survive in the halo of the Milky-Way, amounting to about 0.1% of its total mass. If this were the case, the nearest Earth-mass clump would be on the order of 0.1 pc distant from the Earth and would have a typical size of 0.01 pc. Such nearby clumps might be observable as sources of gamma-rays, produced in dark matter annihilations. They might also contribute to diffuse cosmic ray fluxes of positrons or anti-protons. In order to motivate experimental searches, however, it is important to determine whether the predicted small clumps of dark matter actually survived the grainy tidal

field due to stars while crossing the Galactic bulge and disk ~ 100 times.

In this letter, we estimate of the rate at which Earth-mass clumps are disrupted in stellar encounters. We show that the nearest clumps in a galaxy like the Milky Way are likely to be tidally disrupted by repeated encounters over a Hubble time. Nevertheless, tidal debris from individual clumps may produce distinct microstreams that are potentially observable in dark matter detection experiments.

A Semi-analytic Mass-loss Estimate: In a previous note [2], we presented an analytic estimate for the disruption rate which neglected the internal degrees of freedom available within a microhalo as it responds to tidal encounters. Simulations have long warned (e.g., Moore 1996 [3]) that extended bodies generally have a complex response to external tidal heating, and may lose some fraction of their mass in an encounter rather than being completely disrupted[4]. We can estimate the net result of this more complex process by applying the basic scaling from the semi-analytic mass-loss model of Taylor and Babul [5], which has been shown to provide a good match to self-consistent numerical simulations of mass loss due to tidal heating and encounters.

A typical microhalo in Diemand *et al.* seems to show a core with a maximum central density $\rho_{mic} \sim 10 M_{\odot} \text{pc}^{-3}$ (see Fig. 2 of [1]); for comparison, the density at half-mass radius is much lower, only $\sim 1 M_{\odot} \text{pc}^{-3}$. Thus, it will be strongly shocked even in its central core every time it encounters a star of mass m_* at an impact parameter b_{sh} such that the tidal force, $2Gm_*x/b_{sh}^3$, just exceeds the restoration force, $(4\pi/3)G\rho_{mic}x$, for a small displacement x from the microhalo center. For a rapid encounter with a solar-mass star, $b_{sh} \sim (km_*/\rho_{mic})^{1/3} \sim 0.5 \text{pc}$, where $k \equiv 3(3+e)/4\pi \sim 1$

since the eccentricity $e = 1$ for a radial encounter [7]. According to Taylor and Babul, whenever a system on a general orbit spends time Δt in a strong tidal field, it loses a fraction, $\Delta t/t_{\text{orb}}$, of the mass outside its instantaneous tidal limit, where $t_{\text{orb}} = 2\pi r(t)/v(t)$ is the instantaneous orbital period and the tidal limit is calculated as in the circular-orbit case (e.g. [6, 7]).

A microhalo moving at a relative speed of $V_r \sim 300 \text{ km s}^{-1}$ through a star field with a number density $n_* = \rho_*/m_*$ will encounter stars with an impact parameter $\lesssim b_{sh}$ at a rate of $\dot{N}_{\text{enc}} = n_* V_r \pi b_{sh}^2 \sim n_*/0.004 \text{ pc}^{-3}$ per million years. Each encounter shocks the microhalo for a time $\Delta t = 2b/V_r \sim 3300$ years, and liberates a fraction of the microhalo's total mass. This fraction, from the scaling in Taylor and Babul [5], is roughly $\Delta m/m = \Delta t/t_{\text{orb}} = v_{\text{orb}}/\pi V_r \sim 10^{-4}$. Here, $t_{\text{orb}} \equiv 2\pi b_{sh}/v_{\text{orb}} \sim 30 \text{ Myr}$ is the period of a circular orbit of speed $v_{\text{orb}} = \sqrt{Gm_*/b_{sh}} \sim 90 \text{ m/s}$ around the solar-mass perturber at a distance of $b_{sh} \sim 0.5 \text{ pc}$. Thus, the mass of a microhalo decreases exponentially, with the e-folding time given by $1/\tau \equiv -m^{-1} dm(t)/dt = \dot{N}_{\text{enc}} \Delta m/m = Gkn_* m_* (Gk\rho_{\text{mic}})^{-1/2}$, where we have expressed b in terms of the parameters of the satellite. Averaged over a Hubble time, we find that a microhalo's mass decays exponentially, $m(t) = m_0 \exp(-t/\tau)$, where the e-folding time and the present mass are given by

$$\ln \frac{m_0}{m_{\text{now}}} = \frac{10 \text{ Gyr}}{\tau} \approx \left(\frac{\langle \rho_* \rangle}{0.004 M_\odot \text{ pc}^{-3}} \right) \left(\frac{\rho_{\text{mic}}}{10 M_\odot \text{ pc}^{-3}} \right)^{-1/2} \quad (1)$$

where $\langle \rho_* \rangle$ is the mass density of galactic (disk, bulge and halo) stars averaged along the orbit of a microhalo over the past 10 Gyrs. At earlier times, few stars might have formed. In general, $\langle \rho_* \rangle$ is a function of the pericenter, apocenter and vertical height of the microhalo orbit. A microhalo on a thick disk orbit of height 1000 pc near the solar neighborhood goes through the galactic disk with a mean surface density of $46 M_\odot \text{ pc}^{-2}$ or an average volume density $46 M_\odot \text{ pc}^{-2}/2000 \text{ pc} \sim 0.023 M_\odot \text{ pc}^{-3}$, for example. Thus this microhalo's mass will have decayed by about 6 e-foldings by today (after about 100 disk crossings), and it will be almost completely disrupted. Note that the scaling of Eq. 1 agrees with literature, e.g., Eqs. 6-8 of Ref. [8] or Eq. 8 of Ref. [9].

Numerical Model of Microhalo Orbits: To study the dependence of mass loss on orbital parameters, we have integrated orbits of microhalos in a flattened, axisymmetric galaxy potential with a nearly flat rotation curve: $\Phi(R, z) = (220 \text{ km s}^{-1})^2 \ln \frac{\sqrt{R^2+z^2}/0.8}{\sqrt{R^2+z^2}+60 \text{ kpc}}$. We launch orbits from the solar neighborhood, $(R, z) = (8 \text{ kpc}, 0)$, with a Gaussian velocity distribution (150 km s^{-1} dispersion in each direction). We read off the stellar density along the orbit using the Besancon model of the Galaxy [10], and then take a time average of the star density. The Besancon model is a widely accepted detailed prescription of the number density of stars and stellar remnants of different ages and masses in the Galactic spheroids (bulge and halo) and disks (thin and thick). A

few examples of the microhalo orbits are given together with the star count model in Fig. 1. These simulations suggest that the population of microhalos with apocenters less than 12 kpc has $\langle \rho_* \rangle \gtrsim 0.002 M_\odot \text{ pc}^{-3}$, and are hence past their half-life (green orbit in Fig. 1). The more planar orbits, with $|Z| \lesssim 4(R/20) \text{ kpc}$ and apocenter $R \lesssim 20 \text{ kpc}$ (blue orbit in Fig. 1), have decayed by approximately 1 e-fold with $\langle \rho_* \rangle \sim 0.004 M_\odot \text{ pc}^{-3}$. Complete destruction should happen to disk orbits penetrating into the bulge (e.g., the red orbit in Fig. 1 has $\langle \rho_* \rangle \gtrsim 0.075 M_\odot \text{ pc}^{-3}$, corresponding to about 19 e-folds). In general, we observe a strong correlation between the orbital shape and the disruption rate.

In Fig. 2, we plot the time-averaged stellar density vs. the launch velocity, $|V|$, and its component perpendicular to the plane, $|V_z|$. This plot represents five hundred realizations. There is a clear trend for halos with more planar (smaller $|V_z|$) orbits and orbits with lower energy (hence smaller apocenters) to enter regions of higher density. The sample averaged density is $0.008 M_\odot \text{ pc}^{-3}$ or $0.02 M_\odot \text{ pc}^{-3}$ for median or mean density, so microhalos on Earth-crossing orbits are likely to have been severely stripped. About 10% of the microhalos are in low-density regions (below $0.001 M_\odot \text{ pc}^{-3}$), and might survive more-or-less intact. The chance of survival, however, are likely more severely reduced in the triaxial, barred and evolving potential of the Milky Way, where most orbits are stochastic box orbits which pass through the dense center of the Milky Way at some point over a Hubble time.

We note that the long term fate of the cusp at the very center of each microhalo is unclear. Simulations have shown that systems with a universal density profile may lose all but 0.1–1% of their mass and still retain a bound central region [11]. Such objects may indeed survive to the present-day in the solar neighborhood, but they will have little effect on dark matter detection experiments. The tidal debris stripped out of microhalos may actually be of greater interest, as discussed below.

Implications For Direct and Indirect Detection: As has been pointed out by a number of authors [12, 13, 14], the existence of dark substructure in our galaxy's halo has important implications for the prospects of both direct and indirect dark matter detection. The effect of substructures for direct detection is quite simple: If the solar system happens to be currently located inside of an overdense region of dark matter, then the rate observed by such an experiment will be enhanced proportionally to the density of the clump. If, as is much more likely, our solar system is not inside of such a clump, then the rate will be slightly reduced by the fact that some fraction of the overall density is contained in substructures and thus does not contribute to the density of the smooth component.

To estimate the probability of Earth residing with the volume of a surviving microhalo, note that the number density of more massive clumps is very small in comparison that of smaller substructures ($dN/d\log M \propto M^{-1}$) and thus they contribute very little to the probability of a clump being present in our solar system. Most Earth-mass microhalos have been tidally disrupted, leaving behind only very small and dense cores containing 1–0.1% of their original mass. Es-

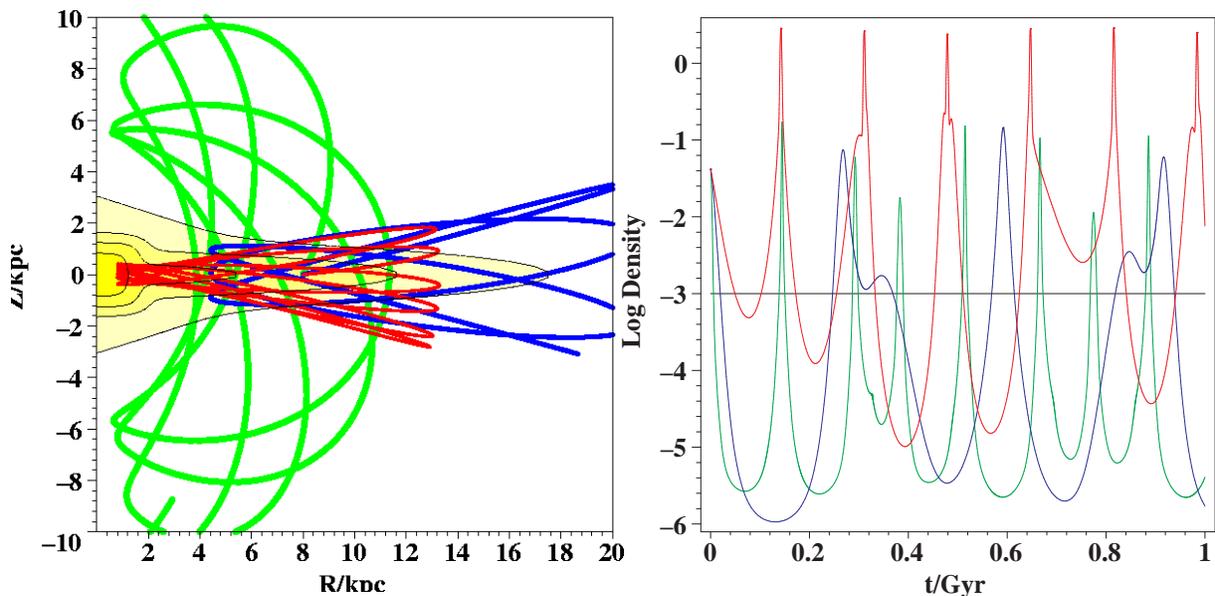


FIG. 1: A cut in the meridional plane of the Besancon star count model of Robin *et al.* [10] (left frame). Contours are shown corresponding to stellar densities of $10^{-i} M_{\odot} \text{pc}^{-3}$ for $i = 0, 1, 2, 3$ with orbits launched from the solar neighborhood overplotted in red, green and blue. In the right frame, the logarithms of the stellar density along the orbits (in units of $M_{\odot} \text{pc}^{-3}$) are shown. The time-averaged densities along these orbits are $0.075 M_{\odot} \text{pc}^{-3}$ (red), $0.0045 M_{\odot} \text{pc}^{-3}$ (blue), $0.002 M_{\odot} \text{pc}^{-3}$ (green).

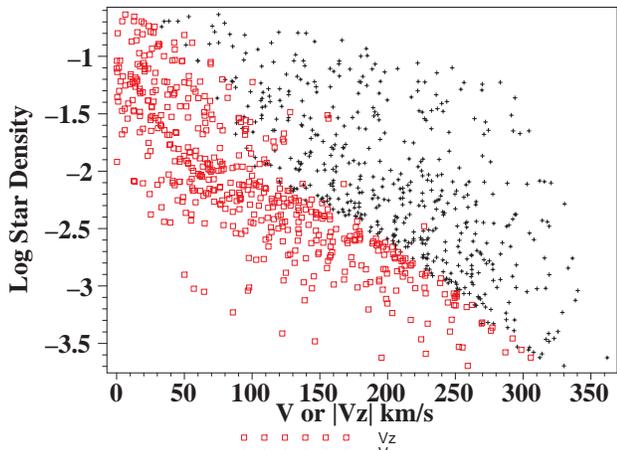


FIG. 2: Log of $\langle \rho_* \rangle$ (in $M_{\odot} \text{pc}^{-3}$, cf. eq. 1) averaged along the orbit vs. the speed (cross) or vertical speed (box) at which the orbit was launched from the solar neighbourhood.

timating a local number density of such cores of around 500pc^{-3} , each with a radial extent of $\sim 5 \times 10^{-5}$ to 1.5×10^{-4} pc, the probability of our solar system residing in such a core is on the order of $\sim 10^{-8}$ to 10^{-10} , and thus compact cores of microhalos are *unlikely* to intersect directly detectors on Earth.

After the effects of stellar encounters are included, however, a third possibility arises. Tidal streams of dark matter generated in stellar encounters may fill a considerably larger volume of space within our galaxy than the original substructures do, and thus are more likely to be intersect the solar system. Tidal debris, leaving a microhalo with a relative escape

velocity of $\sim 1 \text{m/s}$, would travel some 0.1pc along the system's trajectory over the course of $\sim 100 \text{Myr}$ (the time since the previous disk crossing for a microhalo passing through the solar neighborhood). Counting both leading and trailing streams, this means that each disrupted microhalo produces an overdensity $\sim 0.2 \text{pc}$ in length, 10 times the linear size of the original unstripped clump. Given the incidence and duration of clump-crossing events reported by Diemand *et al.*[1], the probability of the Earth being in one of these streams would be $(50 \text{ years} \times 10)/10000 \text{ years} \sim 5\%$. During these periods, the event rate in direct detection experiments would be enhanced by a factor of ~ 10 . Furthermore, the fact that clumps on polar orbits survive longer than those on planar orbits could imprint an interesting directional or phase modulation on the direct detection signal [15].

The implications of dark microhalos and microstreams are rather different for the case of indirect detection. Whereas direct detection measurements are only sensitive to the density of dark matter at the location of the experiment itself, indirect measurements sample the distribution of dark matter throughout larger volumes of the halo. Furthermore, dark matter annihilation rates, and thus indirect detection signals, are proportional not to the density of dark matter, as direct experiments are, but to the dark matter density squared. Substructure within the galactic halo thus may be capable of boosting the dark matter annihilation rate and enhancing the prospects of detecting dark matter indirectly [16].

Techniques employed for the indirect detection of dark matter include gamma-ray, anti-matter and neutrino detectors [17]. Gamma-rays annihilating in nearby and dense substructures, if present, could provide point sources poten-

tially observable by next generation ground or satellite based gamma-ray telescopes [1, 14]. Anti-matter (positrons, anti-protons and anti-deuterons) produced in dark matter annihilations move under the influence of galactic magnetic fields and thus any point sources are concealed and only the diffuse spectrum can be studied. Neutrinos are not as useful for identifying annihilations in the galactic halo, but instead are used to search for dark matter particles annihilating in the core of the Sun. The neutrino flux produced in this way is tied to the local density averaged over very long periods of time and therefore the presence of substructure is of little importance.

Nearby microhalos, being tidally disrupted, are not particularly bright point sources of gamma-rays. For a microhalo's core which retains 1% of its original mass, we estimate that to appear brighter than the dwarf spheroidal Draco in gamma-rays, it would have to be within roughly 10^{-4} pc (tens of AU) of Earth, which is very unlikely.

Anti-matter fluxes produced through dark matter annihilations do not depend on the nature or location of individual dark substructures, but rather on the distribution of dark matter averaged over large volumes. The value of the quantity $\langle \rho^2 \rangle / \langle \rho \rangle^2$, averaged over the contributing volume (a few kiloparces for positrons or tens of kiloparsecs for protons), determines the overall boost factor for the anti-matter fluxes generated through dark matter annihilations.

With a distribution of substructure of the form $dN/d\log M \propto M^{-1}$, each decade of mass contributes almost equally to the boost factor, so it is important to determine over what range of masses substructures can survive. In light of the excess reported by the HEAT collaboration [18], this is of particular importance for dark matter searches involving positrons. To produce such a signal with thermally generated neutralinos, however, boost factors of at least ~ 50 , and typically much higher, are required [19]. Whereas it has been shown that more massive substructures cannot naturally provide such a large boost factor [20], after the effects of tidal disruption are considered, the same is found to be true for Earth-mass microhalos. We agree with previous studies [13] which determine that positron boost factors larger than 2-5 are unlikely. Given this conclusion, another explanation for the excess observed by HEAT appears to be required. Possibilities include the effect of solar modulation on the positron spectrum or the presence of other dark matter candidates which are capable of generating more positrons in their annihilations [21]. Our understanding of these issues will be dramatically improved with data from the up-coming cosmic anti-matter experiments PAMELA and AMS-02 [22].

Conclusions: In this letter, we have discussed the effects of stellar encounters on Earth-mass dark matter microhalos. We have used a semi-analytic estimate of the tidal mass-loss rate, together with numerical integration of representative microhalo orbits, to study the evolution of microhalos crossing the disk of the Milky Way. We find that most microhalos present in the solar neighborhood will have been heavily stripped by stellar encounters, producing 'microstreams' of tidal debris.

More generally, in environments with very low stellar den-

sities such as the outer parts of the Galactic disk or in a Sextans-like dwarf galaxy, microhalos are only mildly heated. But in high-density environments such as the Galactic bulge or an M32-like elliptical (800 to $0.05M_{\odot} \text{pc}^{-3}$ in inner 1kpc of M32 [23]) microhalos are likely fully destroyed. In disk galaxies such as the Milky Way, the fraction of microhalos which are disrupted depends strongly on the orbital inclination and pericentre. Microhalos on orbits coplanar with the disk are very quickly disrupted. Microhalos in the outer part of galaxy halos will encounter far fewer stars, however, and thus their gamma-ray emission may be much brighter. A possible consequence of this might be to detect little gamma-ray emission from the central part of external galaxies, where stars have disrupted most of the dark substructure, and more flux from the outer regions. A ring of gamma-rays surrounding a galaxy, if detected, would provide a strong confirmation of the existence of dark substructure.

The tidal effects discussed in this paper have important consequences for the direct and indirect detection of dark matter. In particular, the probability of the Earth intersecting a tidal stream at any given time is considerably larger than the probability of it being inside a microhalo's core, and thus tidal streams may potentially increase the reach of direct detection experiments. If CDM does produce a detectable annihilation signal, gamma-ray experiments may observe a 'ring' of emission around nearby galaxies. This feature, a consequence of microhalo disruption by stellar encounters in the dense inner regions of galaxies, would be conclusive evidence for the existence of CDM substructure on the smallest scales.

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